

RECONCILING THE GRB RATE AND STAR FORMATION HISTORIES

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ABSTRACT

While there are numerous indications that GRBs arise from the death of massive stars, the GRB rate does not follow the global cosmic star formation rate and, within their hosts, GRBs are more concentrated in regions of very high star formation. We explain both puzzles here. Using the publicly available VESPA database of SDSS Data Release 7 spectra, we explore a multi-parameter space in galaxy properties, like stellar mass, metallicity, dust etc. to find the sub-set of galaxies that reproduce the recently obtained GRB rate by Wanderman & Piran (2010). We find that only galaxies with present stellar masses below $< 10^{10} M_{\odot}$ and low metallicity reproduce the observed GRB rate. This is consistent with direct observations of GRB hosts and provides an independent confirmation of the nature of GRB hosts. Because of the significantly larger sample of SDSS galaxies, we compute their correlation function and show that they are anti-biased with respect to the dark matter: they are in filaments and voids. Using recent observations of massive stars in local dwarfs we show how the fact that GRB hosts galaxies are dwarfs can explain the observation that GRBs are more concentrated in regions of high star formation than SNe. Finally we explain these results using new theoretical advances in the field of star formation.

Subject headings: galaxies: evolution, galaxies: statistics, galaxies: stellar content, gamma-rays: bursts

1. INTRODUCTION

Gamma-ray bursts (GRBs) are short and intense pulses of soft gamma-rays. It is generally accepted that long-duration (> 2 s, but see Bromberg et al. 2012) arise during the Collapse of massive stars the so called Collapsars (MacFadyen & Woosley 1999). This understanding is largely based on the observed association of several long bursts with type Ibc supernovae (SNe) (Hjorth & Bloom 2012).⁴ In such a case, it is only natural to expect that GRBs will follow the cosmic star formation rate (SFR) and that like SNe, their positions within their host galaxies will correspond to the star formation rate within these galaxies. Surprisingly both expectations are not satisfied by observations.

During the last eight years the *Swift* satellite has routinely provided us with accurately localised GRBs. From this data it is possible to construct the luminosity function and cosmic GRB rate. Recently Wanderman & Piran (2010) (WP hereafter) have estimated the rate and luminosity function of long duration GRBs using a novel method that solves simultaneously for the GRB rate and the GRB luminosity function. One of their most interesting findings was that, assuming that the GRB luminosity function does not depend on cosmic time, the GRB event rate does not follow the star-formation rate of the typical galaxy population (their Fig. 9), showing deviations both

at low ($z < 3$) and large ($z > 3$) redshifts. On the other hand, using HST imaging of GRB and SN host galaxies Fruchter et al. (2006) showed that while the likelihood to find a SNe in a given position within its host galaxy is linearly proportional to the SFR at that point, GRBs are much more concentrated within the regions of the highest SFR (see also Svensson et al. 2010).

An obvious question that arises is how these two issues can be reconciled with the idea that long GRBs arise from the collapse of a massive star. A related question is of course what kind of galaxies hosts GRBs and whether the SFR within this hosts is similar to the cosmic one. Ample information is available on the nature of GRB hosts. Inspection of the hosts (Fruchter et al. 1999; Chary et al. 2002; Bloom et al. 2002; Le Floc'h et al. 2003; Tanvir et al. 2004; Fruchter et al. 2006; Castro Cerón et al. 2006; Savaglio et al. 2009); (see also Fynbo et al. 2012; Levesque 2013, for recent reviews) reveals that usually they are low mass irregular galaxies and have low metallicity (Prochaska et al. 2004; Soller et al. 2005; Fruchter et al. 2006; Modjaz et al. 2006; Stanek et al. 2006; Thöne et al. 2007; Wiersema et al. 2007; Margutti et al. 2007; Savaglio et al. 2009; Thöne et al. 2013). These findings are consistent with theoretical modeling that suggests that low metallicity is essential to produce high angular momentum and high-stellar mass needed for GRB progenitors (Yoon & Langer 2005; Woosley & Heger 2006; Wolf & Podsiadlowski 2007). Note, however, that recent observations have revealed a population of more massive GRB hosts (Castro Cerón et al. 2006; Savaglio et al. 2009), in particular when the dustiest galaxies are targeted (Perley et al. 2013). Nevertheless, the fraction of such dusty and massive galaxies is not high enough to reconcile the GRB rate with the typical SFR, at least out to $z=1$ (Perley et al. 2013; Kocevski et al. 2009), i.e. GRBs do prefer galaxies with lower mass with respect to the typical star-forming galaxy popula-

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⁴ Note that it turns out that most bursts associated with SNe are peculiar low-luminosity GRBs that are produced by a different mechanism altogether (Bromberg et al. 2011). However, other evidence and in particular the temporal distribution of long GRBs (Bromberg et al. 2012) provides a direct evidence that long bursts, indeed, arise during the death of massive stars.

tion. As for the metallicity, while GRB hosts typically have low metallicity, a handful of GRB absorbers show roughly solar abundance (Savaglio et al. 2003; Prochaska et al. 2004; Savaglio et al. 2012) or metal enhancement (De Cia et al. 2012).

In an attempt to address the first question we ignore all this information and attack this question using a different approach. Our way to answer the question - which galaxies host GRB - is to have a complete census of star formation histories of all galaxies in the universe and extract the ones that match the observed GRB rate. Here we do it so by exploiting a large SDSS local sample of galaxies and analysing in detail their fossil record. This allows us to effectively have a complete sample of galaxies up to $z \sim 3$ and compare the star formation rate in low mass low metallicity galaxies with the inferred GRB rate.

Once we address this question, we turn to the second question: why are GRBs more concentrated in high SFR rate regions than SNe? To address this issue we make the reasonable assumption that GRBs arise from more massive stars than SNe (Östlin et al. 2008). Following this assumption we compare the positions, within low mass galaxies, of massive ($> 20M_{\odot}$) stars with the positions of less massive ($> 9M_{\odot}$) stars. Finally, we suggest a simple theoretical argument concerning star formation that explains this trend.

2. METHODOLOGY

The spectra of galaxies encodes information about the histories of the component stellar populations, dust, and star formation. Various tools have been developed to extract this information (e.g., Heavens et al. 2000; Tojeiro et al. 2007) and previous works have compared the resulting extracted information with both extrinsic and intrinsic galaxy properties. The MOPED (Heavens et al. 2000) algorithm implements the general process of reforming a complex dataset (e.g., a galaxy spectra) into a set of parameters (e.g., star formation rate, metallicity) and parameter combinations, assuming uncorrelated noise, such that the data compression is loss less.

An easily accessible, robust code, is the VESPA (hereafter VESPA, see Tojeiro et al. 2007, 2009, for more details) package, which recovers star formation and metallicity histories of the galactic spectra using synthetic stellar-population models. The software recovers histories in adaptive age bins according to the signal-to-noise of the galaxy spectrum on a case by case basis and addresses the age-metallicity relation. Two popular synthetic stellar population models are included in the VESPA output, those of Bruzual & Charlot (2003), and the Maraston (2005) & Maraston et al. (2009), which differ in their respective resolutions, and the use of empirical libraries to model the thermally pulsating asymptotic giant branch. Furthermore VESPA corrects for Galactic extinction using the dust maps of Schlegel et al. (1998), and fits for the dust in each galaxy using either a one or two parameter dust model. We exploit the VESPA database to compare the observed GRB rate with that of SDSS galaxies. In particular, we address the question: is there any subset of galaxies from

BinID	$T_B + \text{Bin Start [Gyrs]}$	$T_B + \text{Bin End [Gyrs]}$
0	0.002	0.074
1	0.074	0.177
2	0.177	0.275
3	0.275	0.425
4	0.425	0.657
5	0.657	1.020
6	1.020	1.570
7	1.570	2.440
8	2.440	3.780
9	3.780	5.840
10	5.840	7.440
11	7.440	8.239
12	8.239	9.040
13	9.040	10.28
14	10.28	11.52
15	11.52	13.50

Table 1

The 16 time bins within which VESPA determines the star formation fraction in the rest frame of the galaxy, which corresponds to the time $t = T_B$.

the SDSS that matches the observed GRB rate? If so, what are the physical properties of these galaxies?

3. RESULTS

The $\sim 10^6$ spectroscopically selected galaxies in this work were drawn from the Sloan Digital Sky Survey Data Release 7 (York et al. 2000; Abazajian et al. 2009, and references therein, hereafter SDSS DR7). We selected both “Main Galaxy Sample” and Luminous Red Galaxies (LRG). Galaxy spectra were reprocessed using VESPA and we followed Tojeiro et al. (2009) in adopting the two parameter dust model, but note that our results are insensitive to the choice of dust models.

We are concerned with the star formation histories of galaxies. We extract this quantity from the VESPA database for the highest resolution output (16 bins) in lookback-time bins as specified in Table 1. VESPA also returns the total stellar mass, both present and at formation, of the galaxy and the metallicity for each bin. We explore total mass and metallicity in the VESPA database in order to see if a match is found to the WP data (their fig. 2, upper panel). Note that the derived WP GRB rate shows two characteristic features that do not match the global star formation history of the general population: the peak is shifted to $z \sim 3$ and below that redshift the GRB rate distribution is flatter than the SFR. At high redshift the GRB rate is higher than the SFR rate (see also Jakobsson et al. 2012). From previous experience, we know that this behaviour is a characteristic of low-mass galaxies (Heavens et al. 2004). Fig. 2 in Heavens et al. (2004) shows how the shape and peak of the star formation history of galaxy changes as a function of mass; this already points out to low-mass galaxies as promising candidates. This idea is also supported by the non-detection of extreme-redshift GRB host galaxies in very deep HST imaging (Tanvir et al. 2012). However, in order to find a good match to the WP GRB rate a cut in metallicity is also required. In particular, we find that if we select SDSS galaxies with present stellar masses $< 10^{10} M_{\odot}$ and metallicity $Z < 0.1Z_{\odot}$, we obtain a good match between the GRB rate and the SFR. This means that we need to exclude about half of the dwarfs to obtain such metallicity cut-off (see Fig. 6 in Panter et

⁵ <http://www-wfau.roe.ac.uk/vespa/>

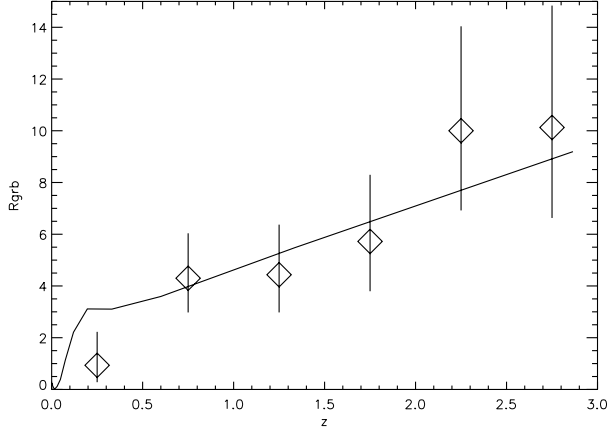


Figure 1. The co-moving rate of GRBs from WP (diamonds) with the best fitting star formation history obtained from exploration of the VESPA catalog. Only after imposing a cut-off in galaxy stellar mass ($< 10^{10} M_{\odot}$) and metallicity ($< 1/10 Z_{\odot}$) one finds a good fit (solid line).

al. 2008). Any other population produces a steeper SFR with redshift and thus cannot be matched to the GRB rate.

Our reported metallicities correspond to the ones of the stellar population in the whole galaxy, as derived by VESPA. These are different from those typically inferred locally for GRB hosts. For example, recently, Graham & Fruchter (2012) have measured the metallicity of the star forming regions (HII regions) in identified GRB hosts. They measure oxygen abundances from emission lines. Their derived metallicities are somewhat larger than ours (by a factor of 50%). This is due to the fact that we measure the whole stellar population, including also the old stellar population in the irregulars, this lowers the overall metallicity (see the blue line of Fig. 3 in Panter et al. 2008). So reporting only the metallicity of the latest and most recent burst in star formation would bring our metallicity in agreement with the metallicity reported by Graham & Fruchter (2012).

Fig. 1 depicts the WP GRB rate distribution with redshift, where the solid line marks the result of our fit. First, note that we could not go beyond $z > 3$ as the VESPA catalog does not contain information on these high-redshift bins. The reason for this is that we are reconstructing the star formation history from the fossil record at a medium redshift of $z \sim 0.2$ and going back so far in time is very difficult. Therefore we limit our analysis to redshifts below 3, not covering the peak of the observed GRB rate. We also note that at low- z the VESPA reconstructed SFR is slightly higher than the WP data at $z = 0.25$, showing a recent bump of star formation activity.

We find that, based just on matching the observed SFR in the specific population of galaxies with the WP GRB rate, the hosts of long GRBs are dwarf galaxies with very low metallicities. This result is in good agreement with direct observations of those hosts (Savaglio et al. 2009), but these samples are limited to a few objects (just 46). In fact, the inconsistency between the GRB rate and typical star formation could have been predicted, given that most GRB hosts are low-metallicity dwarf galaxies with a different SFR than the typical star-forming galaxies

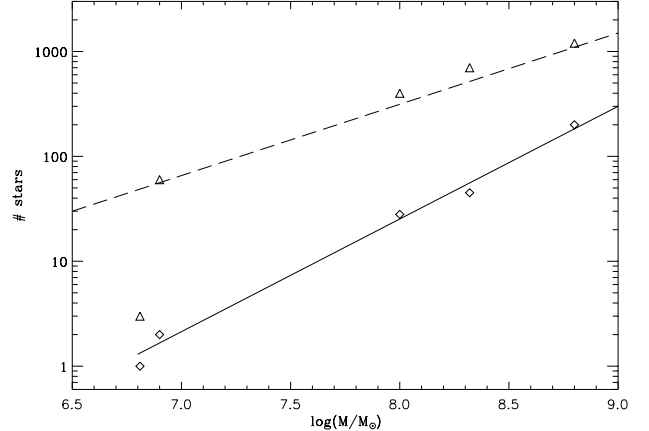


Figure 2. Number of stars as a function of the dwarf galaxy mass for five dwarf galaxies. The diamonds correspond to stars with masses $> 20 M_{\odot}$ while triangles to $> 9 M_{\odot}$. The lines are fits to the data points and show that the more massive dwarfs have more massive stars ($> 20 M_{\odot}$) with respect to less massive stars ($> 9 M_{\odot}$) than lower mass dwarfs.

and hence the overall SFR. The agreement between the metallicity cut in our analysis and the observational evidence that most GRB hosts have low metallicity further supports the WP results on the GRB rate and suggests that the specific nature of GRB hosts rather than a luminosity evolution, for example, is responsible for observed distribution of GRBs redshifts and peak fluxes.

We now turn to the second puzzle, concerning the origin of the discrepancy between the GRB and SN positions within their hosts. To do so we explore the properties of massive stars in these dwarf low-metallicity galaxies. Specifically, we compare the population of massive stars $> 9 M_{\odot}$ with the one of very massive stars $> 20 M_{\odot}$. The basic idea is that while the former lead to SNe, the latter are GRB progenitors and if the two populations are distributed differently this explains the different distribution of GRBs vs. SNe.

The most detailed study of the population of massive stars in dwarfs in the local group is that by Bianchi et al. (2012), who used GALEX observations to determine the number of massive stars ($> 9 M_{\odot}$) in six dwarf galaxies (Phoenix, Pegasus, Sextans A and B, WLM and NGC6822), although for the last one they only have lower limits. We have used the masses for these dwarfs derived by Karachentsev et al. (2004) (column 4 in their Table 4) to plot in Fig 2 the numbers of massive stars as a function of the dwarf galaxy mass. Inspection of Fig. 2 reveals that there is a clear correlation between the number of massive stars and the mass of the dwarf galaxy. Additionally, the ratio $(\# > 20)/(\# > 9)$ of number of very massive to massive stars increases with the mass of the dwarf galaxy. The lines show fits to the data points in Bianchi et al. (2012) and are well fitted by power laws with power 0.7 (for $> 9 M_{\odot}$) and 1.2 (for $> 20 M_{\odot}$), i.e. there is a nearly factor two difference in the power. This empirical observation implies that very massive stars ($> 20 M_{\odot}$) are more abundant in more massive dwarfs. This plot can be compared directly with Fig. 4 in Svensson et al. (2010), which plots the same quantity but for number of SN and GRBs in hosts galaxies. Our results agree very well with the Svensson et al. (2010)

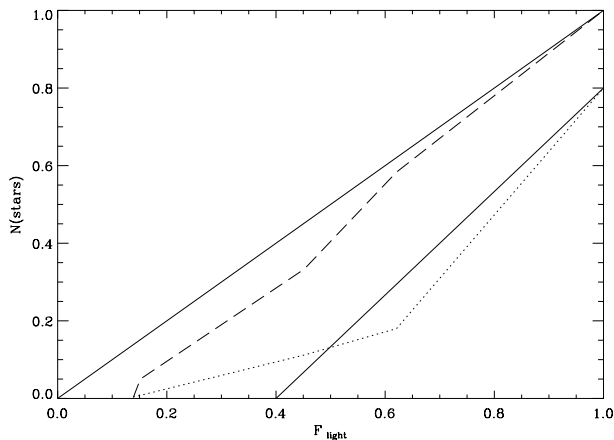


Figure 3. Number of stars with mass $> 9 M_{\odot}$ (dashed line) or $> 20 M_{\odot}$ (dotted line) as a function of the total light in the dwarf galaxy compared with the results from Fruchter et al. (2006) for the numbers of SNe (upper solid line) and GRBs (lower solid line), note the good agreement.

trend. Given that larger dwarf galaxies are denser than lower mass ones, we can take this relation as a proxy to the relation according to which very massive stars are more abundant in denser regions in such galaxies. This assertion, that we will shortly explore further, serves now as the basis for the rest of the analysis.

We can use the data in Bianchi et al. (2012) to produce a plot similar to Fig. 3 in Fruchter et al. (2006), which shows the number of SN/GRBs as a function of the total light in the galaxy. Because we do not have pixel information for the dwarfs, we simply integrate the light in radial rings. This is equivalent to what is done in Fruchter et al. (2006) if the galaxies do not show angular asymmetries, which is the case for the dwarfs we are considering. The results are shown in Fig. 3. The solid thick lines are fits to the Fruchter et al. (2006) results, while the dashed line is the number of stars $> 9 M_{\odot}$ and the dotted line $> 20 M_{\odot}$, where we have averaged over the five local dwarfs: there is good agreement.

Because dwarf galaxies have very low surface density, the outer edges of dwarf galaxies will contain very little mass as compared with the inner part (Tolstoy et al. 2009). For concreteness let us denote as “outer edges” all mass beyond one equivalent radius and as the “inner part” all mass inside it. For dwarf galaxies this means that there is less than a factor 10 mass in the outer edges than in the inner part. If we now use Fig. 2 this means that the outer edges will have a factor 3 less very massive ($> 20 M_{\odot}$) stars relative to massive stars ($> 9 M_{\odot}$) than the inner part. If we now assume that GRBs can only originate on very massive stars then this is in agreement with the observations of the spatial distribution of SNe and GRBs by Fruchter et al. (2006). Thus the fact that GRBs are mostly hosted in dwarf galaxies, when combined with the dependence of the initial mass function on the density in these galaxies, explains also the spatial distribution discrepancy between SNe that follow the local SFR linearly and GRBs that follow the local SFR much stronger than linearly.

It is interesting to explore whether there are any theoretical hints that would suggest this observed “Fruchter et al. law” of a differential initial mass function. The

current consensus (McKee & Ostriker 2007) is that massive stars form because of the turbulent nature of the interstellar medium. Padoan & Nordlund (2002) give a detail theory of star formation due to magnetised turbulence. In particular they predict that the maximal mass of the initial mass function is (their eq. 16):

$$m_{\max} \approx \frac{\rho L^3}{\mathcal{M}_A}, \quad (1)$$

where ρ is the density in the star forming region, L the size of the largest scale where turbulence is driven and \mathcal{M}_A the Alfvén Mach number. It is clear from the above equation that lower density, implies a lower maximum mass. This is the case for dwarf galaxies, in which the density beyond the equivalent radius, is a factor few below that in the inner part (Tolstoy et al. 2009). The size of the largest turbulent scale will remain the same while the \mathcal{M}_A will be similar or slightly larger because of the lower density. Thus, the maximal mass in the outer lower mass region will be lower as observed (see Fig. 2). Note also that the same authors predict that at lower densities the peak of the mass function will move to larger masses, thus increasing the number of SN.

While the above theoretical argument and the observations of massive stars in local dwarf galaxies would suggest that the number of GRBs should equal the number of SNe as the mass of the host galaxy increases beyond $10^{10} M_{\odot}$, it is the metallicity cut-off that prevents this from happening.

4. IMPLICATIONS

The first implication of our results is that, as suggested by direct observations (Graham & Fruchter 2012) and by theoretical arguments (Yoon & Langer 2005; Woosley & Heger 2006; Wolf & Podsiadlowski 2007), low metallicity is an important part of the Collapsar model. While some special cases show GRBs in high metallicity regions, low metallicity is clearly an important factor for most of the population. This has numerous implications on models of GRBs’ progenitors and on the operation of their inner engines.

The fact that low-metallicity plays an important role in the formation of GRBs has also far reaching implication concerning the use of GRBs to explore the early universe. Properly utilising GRBs as probes of the early universe requires a thorough understanding of their formation and the host environments that they sample (Levesque 2013). Galaxies exhibit a strong mass-metallicity relation (see e.g. Fig. 6 in Panter et al. 2008) and massive galaxies ($> 10^{11} M_{\odot}$) do not have such low metallicities as those of GRB hosts. Thus, the host galaxy population of GRBs is biased relative to the overall galaxy population and even relative to the population of dwarf galaxies as we had to impose a metallicity cut of $\approx 1/10$ the solar value, this will exclude about half of the dwarf galaxies as possible hosts of GRBs.

This last point suggests that as we move to the early universe, where metallicity was lower, the GRB rate was much higher and a significantly larger fraction of stars resulted in GRBs. This is consistent with the observation in WP that the GRB rate at high redshifts is significantly flatter than the SFR. Note however, that a massive galaxy will enrich its gas extremely fast (in a dynamical

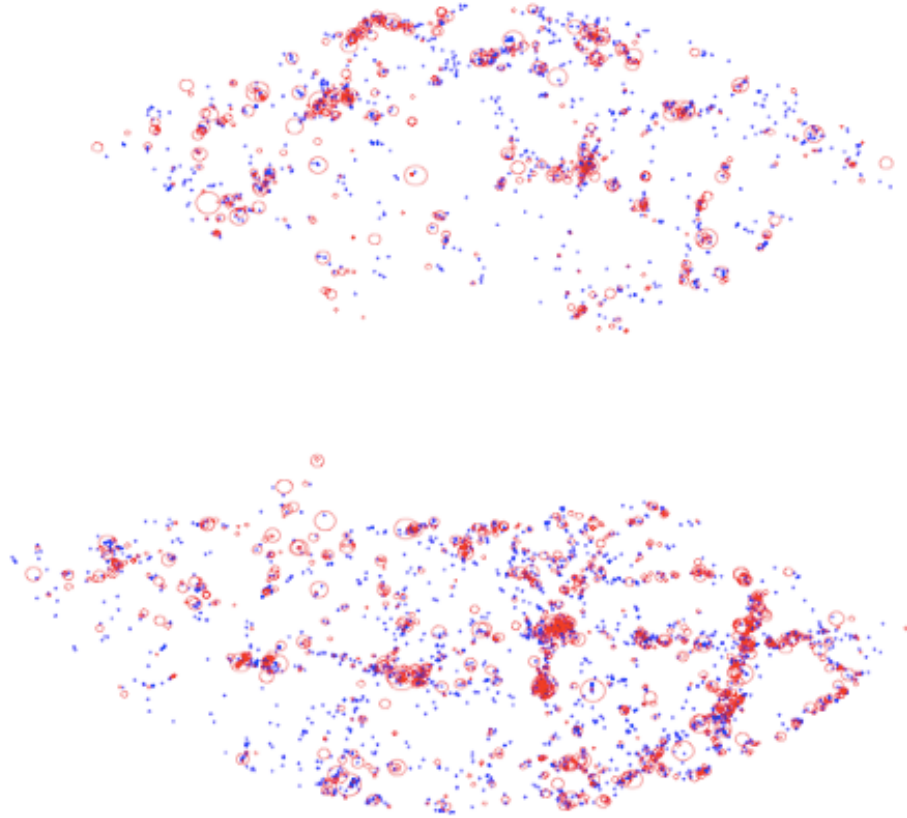


Figure 4. Sky location for the host galaxies of visible GRB, that are needed to match the WP GRB rate, is denoted as blue dots. The lower slice corresponds to $z = 0.1$ and the upper slice to $z = 3$ (assuming the current location). For reference, we also show galaxies classified as luminous red galaxies, i.e. massive ($> L_*$) galaxies with mostly old stellar populations. It is apparent that the hosts of visible GRBs occupy mostly the filaments and voids of the cosmic web.

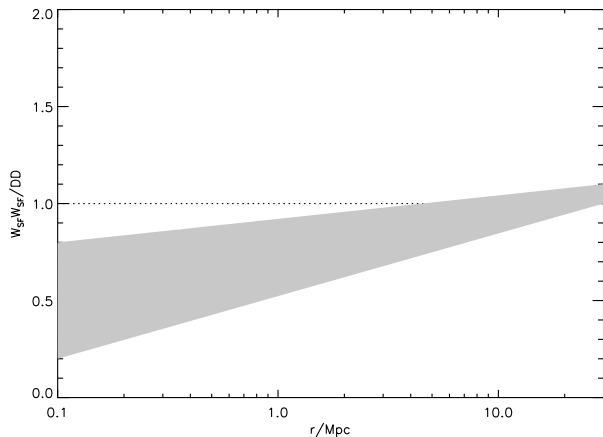


Figure 5. Correlation function for the star formation rate in the hosts of visible GRBs as a function of scale. The grey band shows the computed range for the dwarfs in the SDSS DR7 needed to reproduce the GRB rate in WP. Note that GRB hosts are less concentrated than the mean population (dotted line), thus indicating that their pair separation is larger than the mean of the galaxy population.

time), thus even if the original gas is of low metallicity, only galaxies that have low rates of star formation will be able to host GRBs as they will be able to keep the gas at low metallicity. As we move to lower redshift and the overall metallicity of the gas enriches, even dwarf galaxies will have difficulties at hosting GRBs if they already have

a high metallicity of the available gas to form stars; this explains why the GRB rate decreases at lower redshift. However, because dwarf galaxies dominate the SFR at low- z , the GRB rate will decrease slower than the SFR of the overall galaxy population. If we use the metallicity of the damped Lyman- α systems as a tracer for the metallicity of the gas where galaxies form, we see that at redshift $z \approx 2 - 3$ the metallicity of the gas decreases below 1/10 the solar value (see Fig. 12 in Rafelski et al. (2012)). This same conclusion is obtained if one looks at the metallicity histories of SDSS galaxies (see Fig. 3 in Panter et al. 2008), thus the GRB rate should increase at that redshift in agreement with WP.

After having identified GRB hosts as low-metallicity dwarf galaxies, we can now explore properties of this population within the SDSS data. First, we examine the location in the sky as a function of RA and declination of GRB hosts. Fig. 4 depicts the GRB hosts as blue dots. For reference we have also plotted the locus of luminous red galaxies (i.e. galaxies with larger masses ($\sim L_*$) with older stars in them). It is visually apparent that the hosts of GRBs are situated in the filaments-voids of the cosmic web. The bottom panel of Fig. 4 shows the positions at $z = 0.1$ while the top panel shows their position at $z = 3$ (for this case we have used the current local positions but identified the galaxies according to their star formation history at $z = 3$).

In order to quantify the location in the sky of GRB hosts we compute their correlation function, weighting

by the star formation history, thus we compute the so-called mark correlation, using star formation as a mark. As can be seen in Fig. 5, where the notation WW/DD indicates that the mark statistic is the ratio of weighted pair counts to unweighted pair counts (in this notation, the traditional unweighted correlation function would be DD/RR, where RR is the number of un-weighted pair counts in a random distribution.). The hosts of GRBs are less correlated than the mean population at scales smaller than 20 Mpc. The shaded region shows the 2σ confidence region from all GRB hosts in the SDSS. Our prediction then is that GRBs are to be found in under-dense regions of the dark matter density field, i.e. they will be anti-biased. Most GRBs inhabit regions that show the lowest rates of merging and are undisturbed, despite evidence that some systems do show signs of interaction (e.g., Fruchter et al. 2006).

It is curious to point out that planet formation requires exactly the opposite environment: high-metallicity. Therefore, GRBs overall seem to inhabit regions where no planets form, thus no presenting a risk for life extermination. While this is generically correct all over the universe, it is particularly relevant concerning life extinctions on Earth. The Milky Way is a rather massive galaxy with very few low metallicity regions. In fact, using the star formation and metallicity histories of Milky Way type galaxies (Panter et al. 2008) in the SDSS sample we find that only 2% of the Milky Way has metallicity below of 1/10 of the solar value which we found as typical upper limit to galaxy that host GRBs. This implies that the expected rate of GRBs in the Milky Way is much below the one expected from a simple estimate based on the local cosmic GRB rate per unit time and unit volume ($\sim 1.3\text{Gpc}^{-3}\text{yr}^{-1}$).

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